# A MULTIBODY APPROACH FOR MODELLING OF THE MANOEUVRING AEROELASTIC AIRCRAFT DURING PRE-DESIGN

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## Abstract

*During pre-design, aircraft are described with a limited level of detail, the focus being on fast investigation of a large number of cases and quickly changing configurations and parameters. Therefore in the majority of cases, aircraft are regarded neglecting dynamic aeroelastic deformations. In the paper, an approach to model the aeroelastic aircraft for pre-design based on multibody dynamics is presented. The elastic structure is discretized by the means of rigid bodies, connected by rotational springs to account for wing bending and rotational stiffness. For the aerodynamics, strip theory corrected for the influence of a finite wing is used in the current version. Flight mechanics are included via library elements describing the degree of freedom between the (inertial) reference system and the moving airframe. The complete model allows a free-flight simulation of the aircraft including trim and manoeuvres. The evaluation puts special emphasis on flight load calculation. Scenarios include free flight, a pull-up, and investigations of changes in ground loads due to changes in structural elasticity.*

## 1 Introduction

During pre-design, aircraft are described with a limited level of detail, the focus being on fast investigation of a large number of cases and quickly changing configurations and parameters. Therefore in the majority of cases, aircraft are regarded neglecting dynamic aeroelastic deformations. However, as aircraft become increasingly flexible by new materials and structural optimization, an introduction of aircraft elasticity will greatly increase the reliability of the analysis results even at an early design stage.

An evaluation chain at pre-design usually consists of a number of different methods, including analytical equations (e.g. for range), frequency response (e.g. for handling qualities), and time simulations. In many cases, aeroelastic calculations, load calculation and flight dynamics are treated in separate approaches and independent evaluation modules during the evaluation phase. For time domain analysis, an integrated modelling of flight mechanics and aeroelastic effects is essential. An example is the calculation of dynamic (manoeuvre) loads where an introduction of aeroelastic effects can significantly change the results.

In the European VIVACE project, an Integrated Project running from 2004 to 2007 and combining 63 partners [1], the so-called “Use Case” Prelude is concerned with modularization of the pre-design loop. DLR is working together with Airbus to define and develop a module for non-linear time-domain simulation. The module is based on a multibody simulation (MBS) approach which is well suited for the pre-design task because it is focused on models of medium level of complexity, and because it has inherent capabilities for fast parameter variation and for a simple coupling of engineering disciplines, especially flight mechanics and structural dynamics and aerodynamics [2]. A similar modelling approach is used in the German nationally funded MODYAS project, where the main focus is on integrated modelling for aircraft ground loads. The examples given in the paper are taken from those two projects. As both projects are ongoing, this paper presents the state of work and a preliminary set of results.

## 2 Multibody Simulation in Aircraft Design

### 1.2 Multibody Simulation

Multibody simulation has shown to be a valuable software tool for virtual aircraft design. In aeronautics, it is the state-of-the-art approach especially in the area of landing gear design, ground manoeuvres (take-off, landing, taxiing, ground handling) and the layout of high-lift systems. Comprehensive simulation allows to analyze and to evaluate performance, structural loading and dynamic behaviour of the system. It is becoming more and more important to perform these computations in complex, realistic scenarios; accounting adequately for aero dynamic effects on the flexible aircraft structure is an essential factor for such interdisciplinary simulations.

Another field where a simulation using MBS methods is effective is the coupled aeroelastic simulation of the flying aircraft, i.e. when fluid-structure coupling interacts with flight mechanics and flight control. For this case multibody simulation with its large number of interfaces to other disciplines can be an integrating platform for the multidisciplinary simulation. Such an approach for the aeroelastic simulation of an aircraft has been developed at DLR and has been used in several projects, see [3], [4], [5], [6].

In the VIVACE Prelude Use Case, as well as in MODYAS, a multibody simulation model of a free flying, manoeuvring aircraft is modelled as an example for a modular simulation application. The aim is to determine flight and landing loads on a model of medium complexity which includes an elastic airframe, distributed aerodynamics and realistic flight mechanics. Two test cases have been selected to test the approach and to analyze the difference between calculation of flight and ground loads on a rigid aircraft vs. calculation on an elastic aircraft on a pre-design level.

Multibody simulation has been selected as the method of choice because it is able to include all the disciplines mentioned above in a straightforward manner. Furthermore, the simulation environment can be included in a larger design loop. The multibody simulation tool is SIMPACK, a former DLR development now developed and distributed by INTEC [7]. Some functionalities, e.g. the trim module, have been implemented using the mathematical analysis program SCILAB [8].

The following steps have been taken during the set-up of the simulation cases:

- Data acquisition for the test aircraft, a generic four-engine transport aircraft. This includes aerodynamic data as well as elastic and mass data,
- The set-up of a multibody model of an elastic aircraft using aerodynamic strip theory,
- The implementation of a trim module,
- The simulation of two test cases, a 2.5 g pull-up and a symmetric landing case,
- The output of results in a format usable for the design loop.

### 1.3 Elastic Bodies in MBS

Two approaches are common to represent elastic properties of elastic structures in multibody dynamics. The first approach is probably the older one, representing elastic beams as a combination of rigid bodies connected by torsion springs, see Figure 1. The properties of those springs have to be derived from measurements or available analysis results. The second approach, being the standard one in SIMPACK, makes use of the modal representation of finite element based structures. In a pre-processing step, modal analysis of a finite element structure is performed, and the resulting model is included in the multibody simulation, taking coupling terms between elastic and rigid body motion as well as geometric stiffening and small geometric non-linearities into account [9]. The advantages of the modal approach are that models can easily derived from, often already available, finite ele-

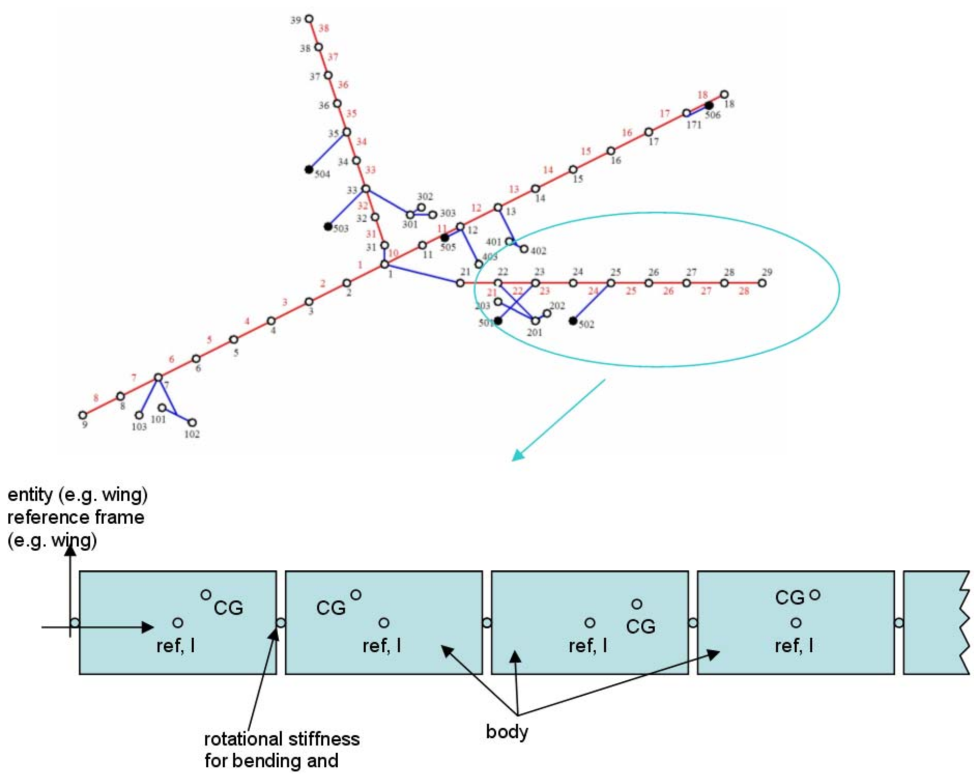

Fig. 1. Layout of multibody model, wing definition and complete aircraft

ment models in a arbitrary degree of complexity. Yet, the modal approach assumes small, linear deformation, whereas in the case of connected bodies no assumptions are made concerning the nature of the connecting force elements. Another reason for choosing the “multiple-body” formulation is that changes in properties of the elastic structure make it necessary to each time repeat all pre-processing steps for the modal approach, whereas for a “multiple-body” approach parameter changes can be quickly made in the MBS model directly.

## 1.4 Application of MBS vs. FEM for Elastic Structures

Finite element (FEA) models are an established way to describe elastic systems. FEA is used for static and dynamic analyses, with models up to a large number of degrees of freedom. Leaving the very time-consuming crash simulation aside, most dynamic applications of FEA use linear models with small deflections, neglecting large rigid body motion. Results of dynamic calculations are often in the frequency domain, i.e. natural frequencies and mode shapes which are input for stability analysis.

MBS codes are generally used for the simulation of complex dynamic systems with large, non-linear motion in combination with reduced elastic models to describe small elastic deformations. Examples are road and wheel/rail vehicles, aircraft and machines. Non-linear forces can easily be described, and the analysis results are typically in the time domain.

The coupling of fluid and structure has become a well developed topic in the finite element world. Consequently, in most applications finite element codes are used for the purpose of fluid-structure coupling. There are, however, a number of reasons to use multibody codes for aeroelastic applications. Most notably, the resulting simulation models in MBS are usually considerably smaller than those of FEA approaches, and are used not only for system evaluation but also as input for control design and real-time applications. However, in most MBS simulations aerodynamic forces are often based on simple assumptions. In many applications, e.g. for automotive, trains, and, of course, aircraft on the ground and in the air, a detailed calculation of the aerodynamic forces is becoming more and more important. For this reason interfaces of the MBS program SIMPACK to aerodynamic codes have been developed [10].

## 2 Model Set-up

### 2.1 Multibody Model Data

#### 2.1.1 Structure

Figure 1 shows the basic layout of an elastic aircraft using a multibody modelling approach. A generic four-engine transport aircraft has been selected as a reference configuration. The structure is discretized in bodies, connected by rotational springs to represent structural elasticity. Input data are the geometry, the discretized mass distribution (mass and local CG with respect to the elastic axis) and the stiffness of the rotational springs connecting the bodies. The data was extrapolated from diagrams of existing aircraft; data was available for wing bending and torsion as well as for fuselage bending and torsion. A typical stiffness distribution for fuselage bending is shown in Figure 2.

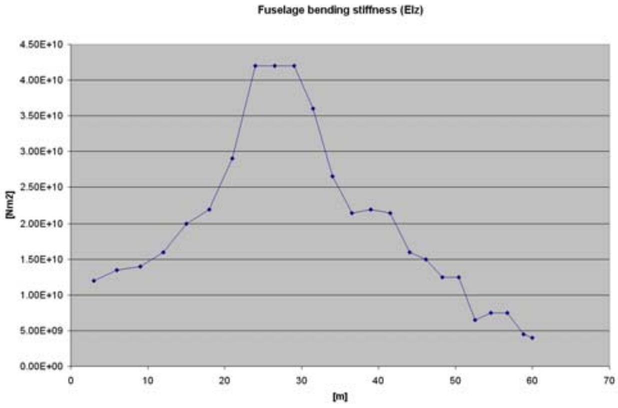

Fig. 2. Bending stiffness distribution of aircraft fuselage

#### 2.1.2 Aerodynamics

For the aerodynamic data, strip theory has been implemented for the first simulation test cases. This method assumes that the aerodynamic properties of the wings can be described in span-wise strips across the wings, not taking any interference between the sections into account. Two-dimensional aerodynamic equations are implemented, using a flat plate assumption, i.e. a linear approach with $2\pi$ as gradient for the dependency of lift from angle of attack. No initial wing twist, i.e. built-in angle of attack, was assumed. The necessary wing reference area for lift calculation was estimated from a top view of the aircraft. Control commands are introduced by changes of the local lift coefficients. For the landing approach, the local lift coefficients have been multiplied by a factor of 1.4 to account for the effect of high-lift devices.

The collected data is coherent. Its accuracy is sufficient to be comparable to real aircraft, if not too close to a real four-engine configuration, e.g. the A340, and sufficient for the determination of trends and comparisons between rigid and elastic modelling approaches.

Figure 3 shows a screen shot of resulting model of the aircraft in the SIMPACK modelling environment.

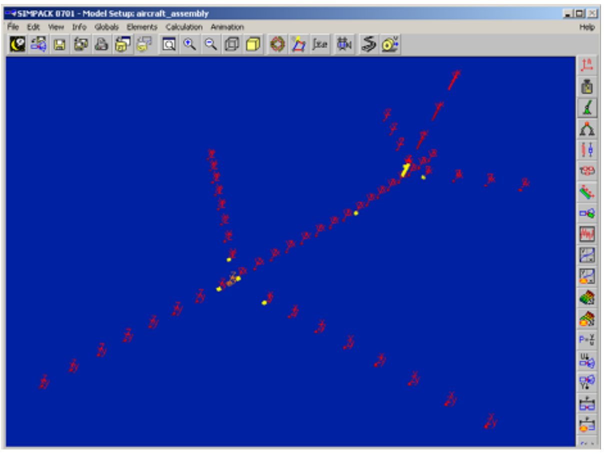

Fig. 3. Resulting multibody aircraft model

### 2.2 Aeroelastic Trim Problem

To be able to simulate a free-flying aircraft it is generally necessary to first solve the so-called trim problem. The trim problem can be characterized in the following way: find a set of suitable input values, e.g. aircraft angle of attack, elevator setting, thrust, to satisfy a set of conditions, e.g. to fly in a straight path in steady state, i.e. no accelerations along x, z, and no rotational acceleration around y. For the trim calculation the representation of elastic bodies in multibody simulation is well suited. The number of degrees of freedom describing the elastic structure, i.e. the elastic states, is of the same order of magnitude as the flight mechanics and/ or flight control states. For the elastic aircraft, an additional condition to the conventional trim requirements is that the elastic deformation is in steady state, i.e. the second derivatives of all body motion representing the elastic structure have to be zero.

The general trim approach is independent of the chosen aerodynamic representation. If an internal aerodynamic model is chosen, the solution of the trim equations inside the MBS is straightforward, the conventional solver to calculate equilibrium for the mechanical model can be used. If an external program for aerodynamics is chosen, e.g. if a co-simulation between MBS and CFD is used, the data exchange is not controlled by a time stepping integration scheme but rather by the non-linear equation solver used for the trim module. During the trim calculation, the trim solver selects a set of values for the inputs, the MBS program evaluates the right-hand-side as function output and supplies the solver with the solution. The solver then in turn selects a new set of input variables until it is close enough to the final solution. For the trim calculation, the co-simulation has to be performed each time the trim solver requests a new function value.

While SIMPACK is equipped with an internal trim module, an external solution has been chosen for the given examples. A trim routine has been implemented in SCILAB based on the evaluation of time simulation results. The approach is the following: for a given set of parameters (speed, angle of attack, elevator setting) a time simulation is performed, holding the parameters constant. The air speed is constant, no further rigid body aircraft motion is allowed w.r.t. the inertial system. However, the elastic degrees of freedom are free to move to their respective equilibrium positions. When the structural vibrations have been damped out, the simulation stops. The constraint forces between the aircraft rigid body and the inertial system, necessary to hold the aircraft in its pre-described position and attitude, are then used as input for the trim algorithm. The algorithm changes elevator setting and angle of attack until all constraint forces have been brought to zero. The advantage for this scheme against the conventional method is that not all of the equations of motion have to be known beforehand. The method handles arbitrary properties of the interaction of structure and fluid which need not be known to the trim solver at the formulation of the trim problem.

## 3 Simulation Cases and Results

Results for two manoeuvres will be shown here for a demonstration of the work flow, a 2.5 g pull-up and a two-point landing with a vertical touch-down velocity of 3.05 m/s.

### 3.1 Pull-up manoeuvre

As an example for the coupled simulation, a 2.5 g pull-up has been defined. The simulation has been performed both with a rigid and with an elastic aircraft. One goal of the simulations is to assess of the differences between the two approaches, most notably to see whether an elastic model has an influence on the prediction of the dynamic loads at the wing root. The comparison shows exemplarily the differences between the two modelling approaches.

The simulated aircraft has a weight of 180 t and is calculated starting with a steady flight from trimmed conditions:

- vx = 200 m/s
- elevator setting: 10.2 deg.
- angle of attack: 1.85 deg

In the simulation, the elevator setting is changed from 10.2 deg such that an acceleration of the center of gravity of 2.5 g is reached. The elevator input has to be different for the rigid and the elastic model as both aircraft react differently to the input. Figure 4 illustrates this fact. In Figure 4, top, the commanded elevator deflection to achieve the required 2.5 g is shown for a rigid and an elastic aircraft. Due to the structural response a higher elevator deflection has to be commanded for the elastic aircraft than for the rigid one to achieve the same CG acceleration for both cases. As shown in Figure 4, bottom, the

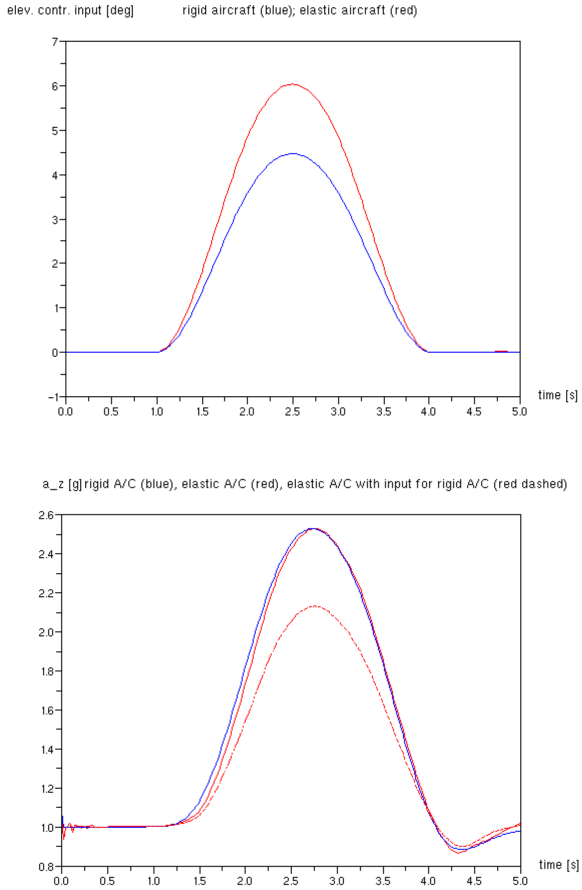

Fig 4. Elevator deflection and aircraft response (acceleration at aircraft CG) for rigid and elastic aircraft

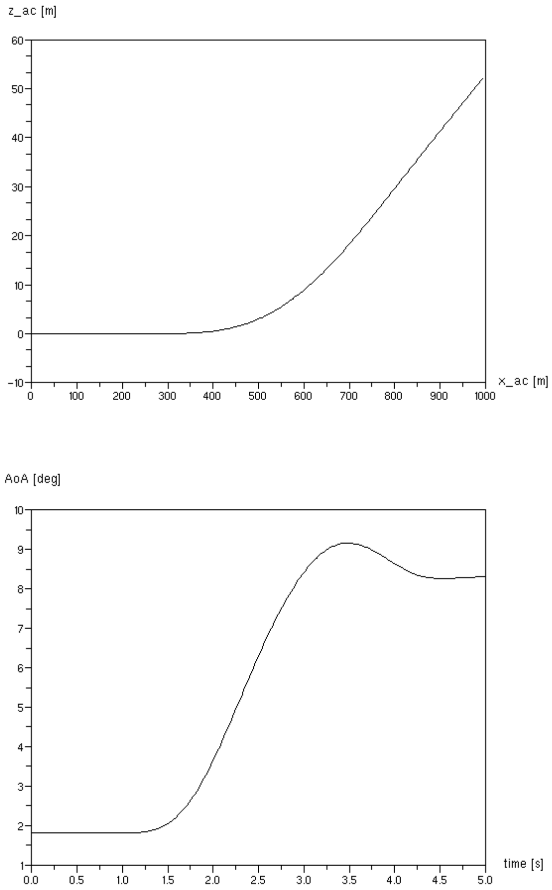

Fig. 5. Aircraft CG position and angle of attack during 2.5 g pull-up

response of the elastic aircraft is about 25% smaller than for the rigid aircraft if the same elevator command is used.

In Figure 5, the position and the angle of attack of the aircraft is displayed. Using the respective inputs shown in Figure 4, both aircraft have roughly the same overall system response. While the airframe dynamics have an influence on the rigid body flight mechanics, the differences are so small that they are not visible in Figure 5.

Wing deflection and aerodynamic load distribution are shown in Figure 6. In Figure 6, top, the initial wing deflection is the reference shape, i.e. the flight shape in steady cruise (1 g, black line), the red line is the new deflection under the air load at 2.5 g. The rigid aircraft shows no deflection against the reference shape, of course.

In Figure 6, bottom, the lift distributions are compared, at cruise (black line, equal for rigid and elastic aircraft), and at 2.5 g (blue line for rigid, red line for elastic aircraft). The elastic twist bends the wing upwards and, because of the wing sweep, introduces a downward tilt of the profile, effectively reducing the local angle of attack and thus the local air force on the outboard part of the wing. The effective aerodynamic center is therefore shifted inwards for an elastic wing when compared to a rigid wing. This effect leads to a significantly lower wing root bending moment of the elastic aircraft when compared to the rigid model, in the current setup the difference is approximately 20%, see Figure 7.

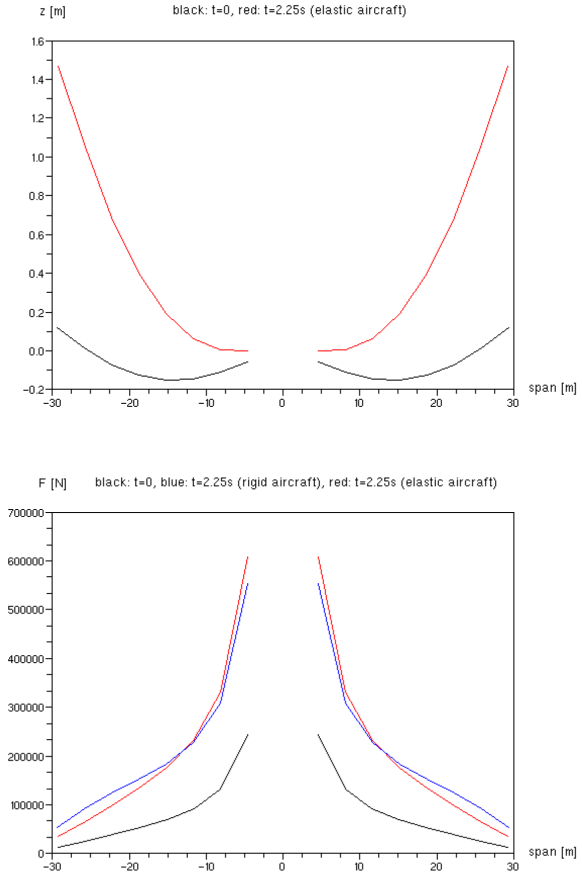

Fig. 6. Wing deflection and aerodynamic load distribution for rigid and elastic aircraft

Thus, for the given flight conditions and control input, a reduced calculated root bending moment can be shown for an elastic aircraft against a rigid one. This fact indicates that for most cases, a rigid simulation gives conservative load assumptions. However, this assumption might not be valid for gust or control excitations in the frequency range of the wing or fuselage natural frequencies, where elastic models might exhibit higher responses.

## 3.2 Touch-down Manoeuvre

A second study has been performed with an aircraft descending with a vertical velocity of 3.05 m/s, an important certification case for landing gear and aircraft design. The aircraft is the same one as above, i.e. with a mass of 180 t.

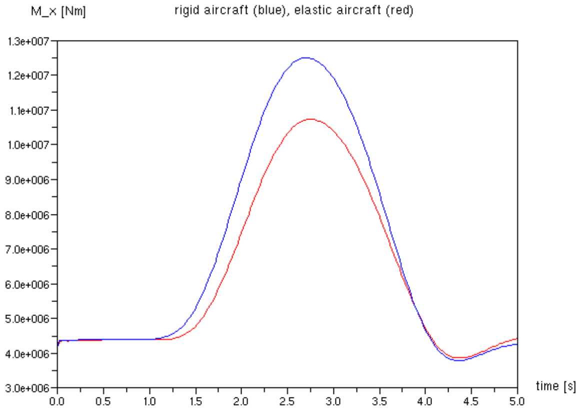

Fig. 7. Calculated root bending moment for rigid (blue) and elastic (red) aircraft

The approach is a descend with a vertical velocity of 3.05 m/s (10 fps) and a forward velocity of 55 m/s with a pitch angle of 12 deg, i.e. an effective angle of attack of 15.2 deg.

Four configurations have been compared:

- a rigid aircraft in flight shape,
- an elastic aircraft with nominal wing attachment stiffness,
- an aircraft with half the nominal attachment stiffness,
- an aircraft with 1/4 of the nominal attachment stiffness.

Figure 8 shows the configuration of the landing aircraft.

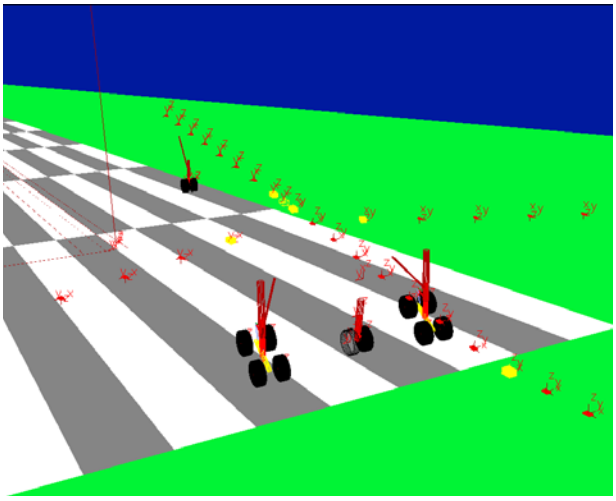

Figure 8: Multibody model of the aircraft at touch-down

The results are plotted in Figures 9 and 10. Figure 9 shows the vertical acceleration at CG of the rigid aircraft at touch-down. The acceleration reaches approximately 2.4 g, which is comparable to the flight manoeuvre described above. The acceleration displays two peaks which is due to the characteristic of the landing gear, see Figure 8.

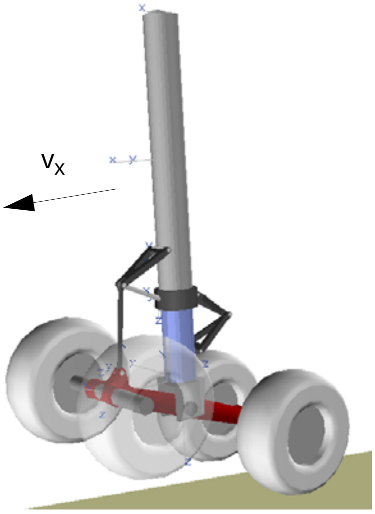

Fig. 8. Aircraft main landing gear

The rear wheels of the landing gear touch the ground first, pushing up the tilted bogie of the landing gear while absorbing energy; the compression of the shock tube fully starts after all wheels of one landing gear have touched down. This behavior leads to a characteristic of a two stage spring and shock absorber.

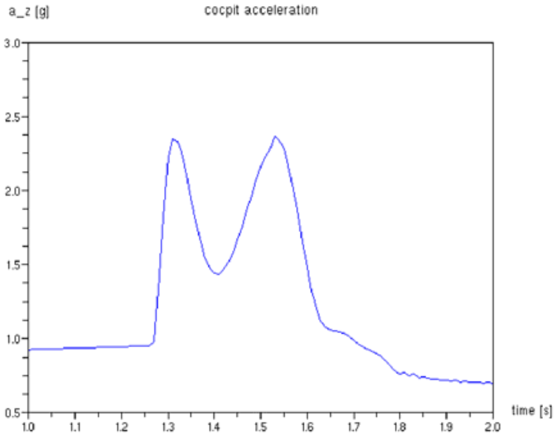

Fig. 9. Cockpit acceleration at touch-down

Both load peaks can be found in the response of the moment in the wing root. The comparison between rigid and elastic modelling displays several dynamic effects. First, the flank of the load increase is much steeper for the rigid model than for the elastic models. The load of the first peak diminished with increased elasticity. However, the second load peak, approximately 0.25 s after the initial peak, reaches amplitudes comparable to that of the first peak for all elastic models, with a tendency of higher loads for the more elastic attachments. Finally, a phase shift between the rigid and the elastic models is visible.

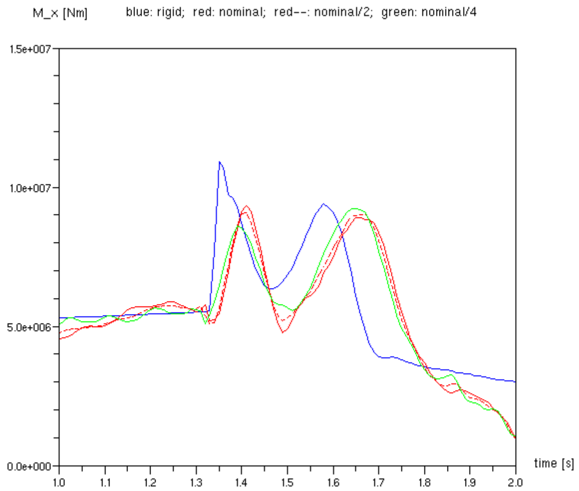

Fig. 9. Calculated root bending moment for touch-down, rigid (blue) and elastic (red / dotted red / green) aircraft

Summarizing, as in the case of the 2.5 g manoeuvre, it can be said that for most cases an elastic model will exhibit lower loads than a rigid one. However, in the example of the touch-down, the dynamic effects could be shown to increase the calculated loads under certain circumstances. A similar observation has been made for ground runs of aircraft in [11], where rigid modelling underestimated the dynamic aircraft response by a factor of up to three.

Both simulation cases showed significant differences between the results calculated for elastic and rigid aircraft, even for relatively preliminary modelling. Consequently, it can be stated that taking aircraft elasticity into account will give valuable insight even at an early design stage. The additional information more than balances the additional effort needed for the implementation of elastic models and the respective simulation capabilities.

## 4. Outlook

The next step for the multibody simulation application will be the implementation of an interface to a higher-order aerodynamics method. Two variants are in preparation, the coupling to the lifting line method and the coupling to a surface panel method, both quasi-steady methods. A coupling to an unsteady panel method is also planned.

In parallel, the simulation will be introduced into a structural sizing loop. The approach is to use realistic loads from simulations taken from the flight envelope in an external structural sizing tool. This tool, based on a beam approach, will give back elastic properties and masses of the wings which will be used to modify the simulation model, which will then re-run the load simulations.

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